



U.S. ARMY TANK AUTOMOTIVE RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

Mobility Research at TARDEC

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- Roadmaps for
 - Off-road mobility
 - Intelligent mobility*
 - Automotive Research Center (ARC)*
- Research activities at TARDEC
 - Tire, track, and soil modeling
 - Numerical methods and scalability
 - Next-Generation NATO Reference Mobility Model (NRMM) Team
 - Autonomy-enabled UGV mobility*
- Funding
 - No CREATE-GV funding used
 - Very limited TARDEC funding
 - Leveraged funding through SBIR, STTR, RIF, ARC, etc.
- Benefits
 - Feeds into CREATE-GV and ERS
 - e.g. Chrono software transitioned to CREATE-GV as vehicle dynamics engine

*Time permitting

The diagram illustrates the components and modeling approaches in Offroad Vehicle Mobility Research, organized into three main domains: Vehicle, Vehicle-Terrain Interface, and Terrain.

Vehicle Domain

- Dynamics**
 - Chassis
 - Powertrain
- Structure**
 - Rigid
 - Deformable
 - Small
 - Large (UIC)
 - Parallel (UWM)

Integration: A red double-headed arrow labeled "Integration" connects the Chassis/Powertrain and Structure domains.

Vehicle-Terrain Interface Domain

- Track Model**
 - Super Element
 - Multi-Link Rigid
 - Multi-Link Flex (UIC)
 - Band Track (UIC)
- Tire Model**
 - Spring-Damper
 - Integrated FEM (UI)
 - Parallel (UWM)

Terrain Domain

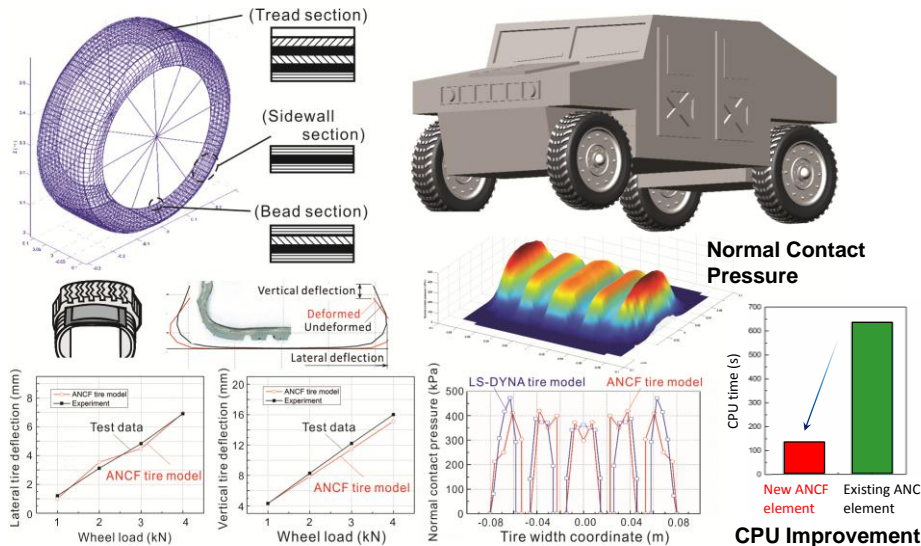
- Empirical**
 - NRMM
 - Bekker
- Semi-Empirical**
 - NextGen NRMM Threshold (Wong)
- Physics-Based**
 - Sand: DEM (UWM)
 - Loam: FEM (UIC)
 - Clay: MFM (UWM)

Modeling Approaches: A vertical bar on the right side of the diagram categorizes models as UWM (Unified Whole Model), UIC (Unified Interface Component), or Parallel.

LJWM

Gap

Tire – Soil Simulation, A Flexible Multibody Dynamics Approach



Purpose

Develop physics-based high-fidelity tire/soil interaction simulation capabilities using the absolute nodal coordinate formulation (ANCF) and integrate into the high performance computing (HPC) off-road mobility simulation framework with deformable terrains.

Leap-ahead/Disruptive Products/Results

- Novel physics-based high-fidelity deformable tire models based on advanced flexible multibody dynamics formulations – ANCF tire model
- Accurate and efficient ANCF deformable terrain model for off-road mobility simulation
- High-fidelity physics-based ANCF tire/soil interaction simulation capabilities fully integrated into HPC off-road mobility simulation framework
- Robust and efficient GPU computing algorithms for the ANCF tire/soil interaction simulation

Payoff

Novel physics-based HPC modeling and simulation capabilities for tire/soil interaction using advanced flexible multibody dynamics formulations.

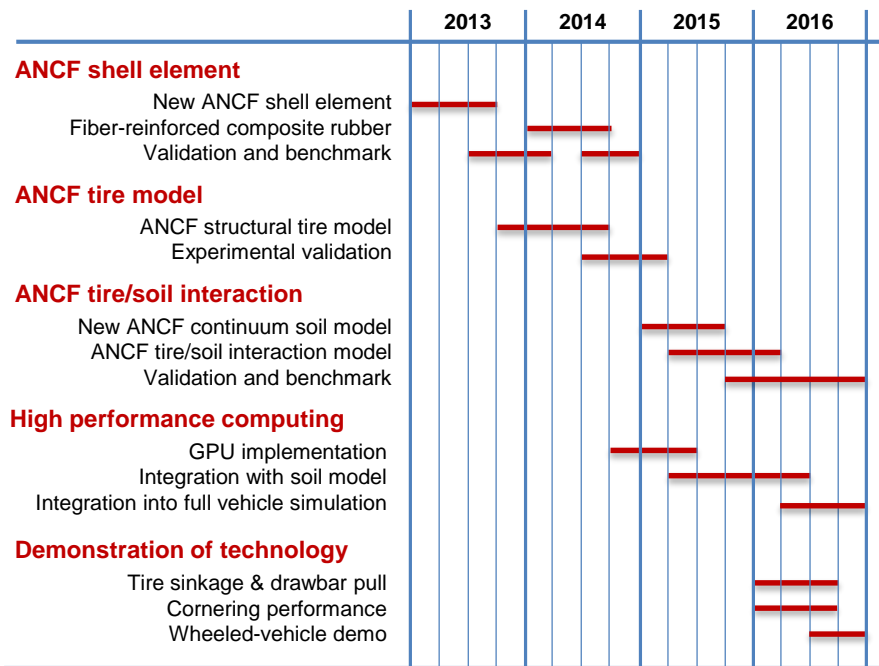
Enable demonstration of mobility capability that includes

- Maneuverability of military ground vehicles on deformable terrains
- Mission-specific power requirement
- Virtual prototyping and design analysis for improved mobility

Transition Milestones

- Deliver HPC ANCF tire/soil interaction simulation codes for ground vehicle mobility [December 2016]
- Deliver ANCF tire and ANCF soil models for HPC off-road mobility simulation [December 2016]
- Transfer technology to third-party software and industrial partners [ongoing]

POC: Dr. Paramsothy Jayakumar, TARDEC
Dr. Hiroyuki Sugiyama, University of Iowa



Track - Soil Modeling and Simulation Using ANCF Finite Element



Vehicle/Soil Interaction



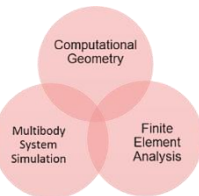
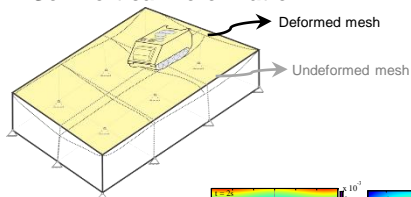
ANCF Leaf Spring models



FFR/FE Mesh/Liquid Sloshing



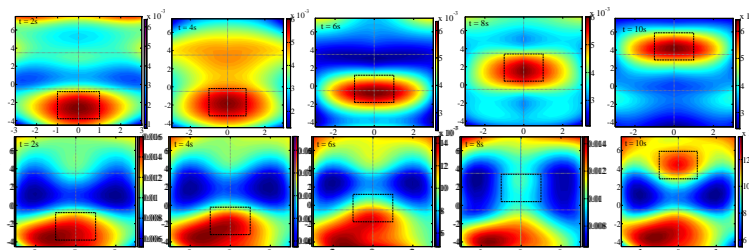
Soil Vertical Deformation



Flexible Link Chain



Elastic Soil



Drucker-Prager Elasto-Plastic Soil

	FY14	FY15
Modeling capabilities		
FFR element library		
ANCF element library		
Rigid and flexible body models		
Comprehensive joint and force library		
Solver capabilities		
Explicit and implicit solvers		
Advanced and flexible body models		
Integration of FE/MBS algorithms		
Implementation issues		
Sparse matrix techniques		
User interface and documentations		
Visualization		
Mesh graphics and mode shape anim.		
Model animation and stress display		
Validation		
FFR models		
ANCF models		
Tire-leaf spring models		
Demonstration of technology		
Tracked-vehicle demo		
Wheeled-vehicle demo		
Liquid sloshing demo		
Railroad vehicles demo		

Purpose

Develop new generation of MBS software technology for vehicle mobility based on new geometry concepts and numerical approaches

Leap-ahead/Disruptive Products/Results

- High-fidelity vehicle models with significant details that cannot be captured using existing MBS and FE tools.
- Effective integration of FE and MBS simulation capabilities in one tool
- Building the foundation for integrating CAD, FE, and MBS codes into one software
- **Ability to develop unique and new continuum-based small and large deformation models for soil, tires, leaf springs, liquid sloshing,...**

Payoff

New generation of MBS software technology that will allow for efficient virtual prototyping and for eventually integrating geometry and analysis. The results are:

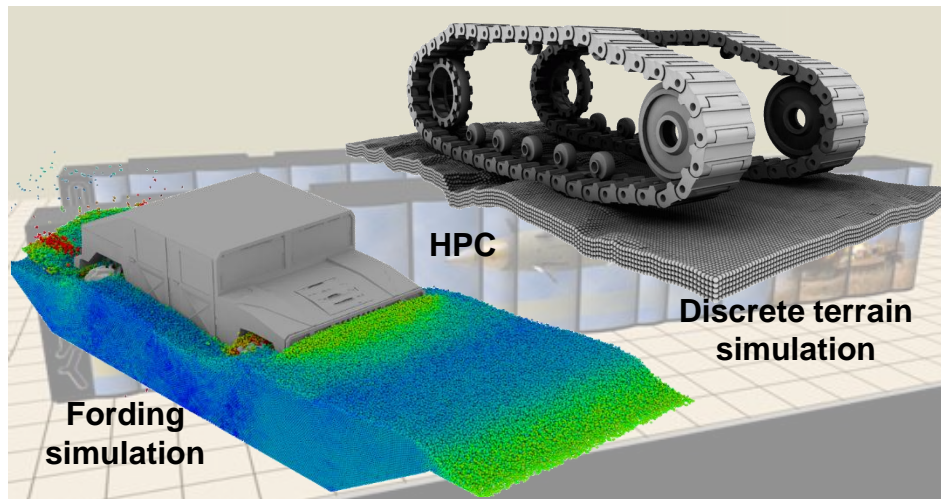
- Integration of FE and MBS software for vehicle mobility
- Replacing 30-year old formulation MBS software
- Advanced tools for vehicle mobility which will reduce the exorbitant maintenance cost.

Transition Milestones

- A copy of the Sigma/Sams software was sent to TARDEC in order to obtain feedback on the developments [January 2015]
- Develop toolkits for different vehicle types to allow the user to easily build complex vehicle models [December 2015]
- Work on the code packaging and commercialization [ongoing]
- Work with TARDEC engineers and industry to ensure effective technology transfer [ongoing]

POC: Dr. Paramsothy Jayakumar, TARDEC

Dr. Ahmed Shabana, Univ. of Illinois at Chicago / Computational Dynamics Inc.



Purpose

Develop scalable, physics-based HPC modeling, simulation, and visualization capability for analysis of ground vehicle mobility on deformable terrain

Leap-ahead/Disruptive Products/Results

- High-fidelity wheeled and tracked vehicle modeling with rigid and deformable components
- High-fidelity, physics-based deformable tire models
- **Robust and scalable numerical methods for solving billion-body frictional contact problems**
- **Very large scale simulations of multi-physics vehicle mobility scenarios on massively parallel architectures**

Payoff

Unique capability for scalable, efficient, and accurate multi-physics, multi-discipline HPC simulation of ground vehicles and terrain-vehicle interaction. Enable maneuverability prediction studies at unprecedented levels of fidelity:

- Terrain trafficability for various soil conditions
- Mission-specific power requirement analysis
- Virtual prototyping and design analysis for improved mobility

Transition Milestones

- Deliver an open source HPC computational dynamics capability for ground vehicle mobility scalable to tens of thousands of nodes [August 2016]
- Deliver a collection of wheeled and tracked vehicle models for multi-physics simulations of mobility over deformable terrain and fording analysis [May 2016]
- Organize RIF-centric consortium meetings and hands-on tutorials [biannual, May & December]
- Transfer of technology to third-party software and industrial partners [ongoing]

POC: Dr. Paramsothy Jayakumar, TARDEC
Dr. Dan Negrut, University of Wisconsin-Madison

	FY15	FY16
Modeling capabilities		
ANCF Tire model		
Terramechanics		
Tire/soil interaction models		
Corotational FEM		
Solver capabilities		
Parallel DEM solver		
Implicit FSI		
Parallel linear solver		
HPC implementation		
Heterogeneous HPC (DEM)		
Heterogeneous HPC (FSI)		
Visualization		
Graphics as a service		
Advanced visualization plugin		
Validation		
Soil models		
ANCF tire models		
Tire-soil interaction		
Demonstration of technology		
Wheeled-vehicle demo		
Tracked-vehicle demo		
Liquid sloshing demo		
Fording scenario demo		

Next-Generation NATO Reference Mobility Model Team



- Goal
 - Physics based simulation, not empirical as current NRMM
 - Address contemporary vehicle design technologies
 - **Develop specifications that promote standardization, integration, modular interoperability, portability, expansion, verification and validation**
 - Tool choices meeting the standards can be government, commercial, open source, etc.
 - NATO level engagement
- Nations participating: 15 Number of members: 41
- Lead Nation: USA
Co-Chair: Dr. Paramsothy Jayakumar (USA), Dr. Michael Hoenlinger (Germany)
AVT Panel Mentor: Dr. David Gorsich, USA
- Monthly teleconferences and bi-annual NATO meetings held
- 7 Themes Lead Organization

1: Requirements	Jody Priddy	ERDC
2: Methodology	Dr. Mike McCullough	BAE
3: Stochastics	Dr. Karl Iagnemma	MIT
4: Intelligent Vehicle	Dr. Abhi Jain	NASA JPL
5: Tool Choices	Henry Hodges	NATC
6: Input Data & Output Metrics	Brian Wojtysiak /James Ngan	AMSAA
7: Benchmarking	Rainer Gericke	Germany

NextGen NRMM Methodology Development Vision



Model Component	Model Fidelity and Resolution			
	Empirical – Current NRMM	Empirical - Enhanced	Open Architecture Model NORMMS	
			Threshold (Semi-Analytical)	Objective (Analytical)
Mobility Mapping	NRMM Operational Module	NRMM Operational Module	Modified NRMM Operational Module	Modular, Expandable, Documented, Verified, Mobility Mapper with Long Term NATO CM support
Off-Road Mobility	NRMM	NRMM+	Bekker/Wong Terramechanics	FEM / DEM / MFM
Vehicle Dynamics	VEHDYN (2D)	3D MBD	Ftire, Multilink track	Integrated deformable, dynamic terrain
Intelligent Vehicle	Constant speed	Variable speed	Closed loop 3D path following with sensors	Autonomy with analytical sensor-terrain interaction in feature rich environments
Compute Platform	Desktop	Desktop	Multi-Threaded Desktop	HPC

LEGEND

Requirements

NORMMS Specs

MBD Model S/W

Terrain Data

H/W

NORMMS: NATO Operational Reference Mobility Modeling Standards

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FY15

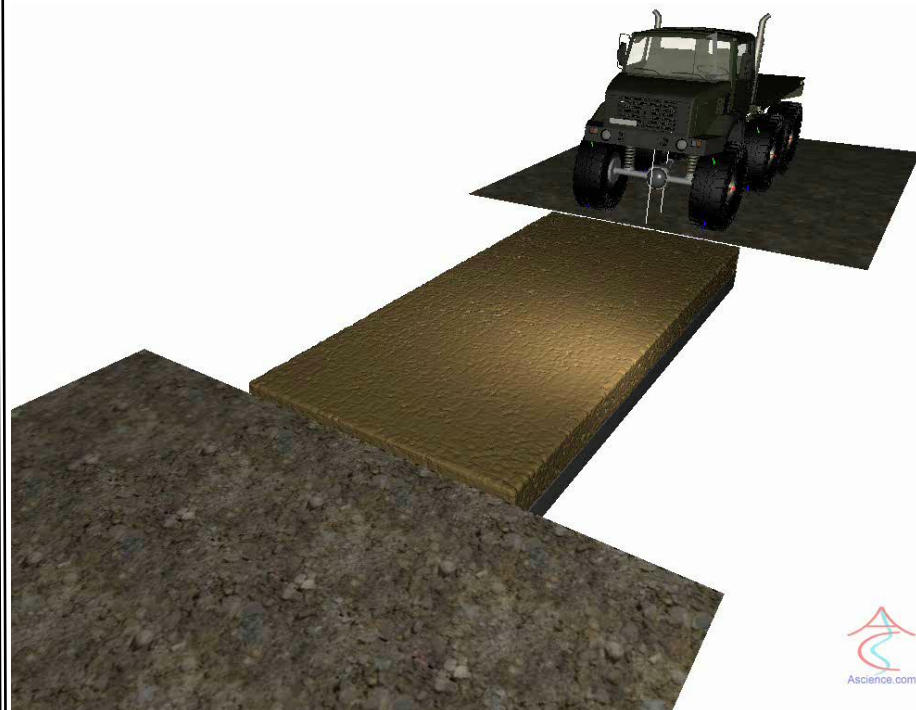
#	Task Month	1	2	3	4	5	6	7	8	9	10	11	12
1	Familiarization with NRMM (TARDEC and ASA)												
2	Calibrate the Soil Model (ASA and TARDEC)												
3	Create the HMMWV Vehicle model (TARDEC)												
4	Create a Terrain Map Converter Program (ASA)												
5	DIS Software Installation on the HPC (ASA)												
6	Create a Program to Automate running DIS on the HPC (ASA)												
7	Run the NRMM simulations on the HPC (TARDEC)												
8	Develop a Program to Automate Post-Processing of the Simulation Results (ASA)												
9	Simulation verification (TARDEC)												

Purpose

Develop a NRMM-like Mobility Map using a Coupled Finite Element Vehicle Model, a Discrete Element Soil Model, and an HPC System in support of the NATO Exploratory Team on NextGen NRMM Development.

Leap-ahead/Disruptive Products/Results

- Explicit parallel solver with fully-coupled Flexible multibody dynamics (FMBD), discrete element method (DEM), and smoothed particle hydrodynamics (SPH).
- General elasto-visco-plastic-frictional DEM particle force model for modeling cohesive and non-cohesive soils.



Intelligent Vehicle Mobility Simulation Roadmap



KO: 1.1.1, 1.1.4

Model-Based Development of Mobility vs. Autonomy Relation

Platform Mobility

TARDEC

Mobility Scenarios Selection

TARDEC

Mobility Metric Selection

TARDEC

Dynamic Model Fidelity Decision



Dynamics Solver Selection

JPL

Terramechanics Approach Development

NATO

Compute Power Selection

ARL TPA

Simulate Mobility Events

TARDEC

Communication

CERDEC

Communication Network Selection

CERDEC

Identify Delays and Bandwidth Issues

CERDEC

Implement Delays

UM

Simulate Mobility Events for Various Delays

TARDEC

Analyze Effect of Delays

TARDEC

Mitigate Effect of Delays

UM

Autonomy

UM

Select Framework for Shared Control

MIT

Control Algorithm Selection

UM

Driver Cognitive Model Selection



TARDEC

Sensor and Perception Algorithm Selection

ERDC

CERDEC

Identify Delays

UM

Simulate Mobility Events for Levels of Autonomy

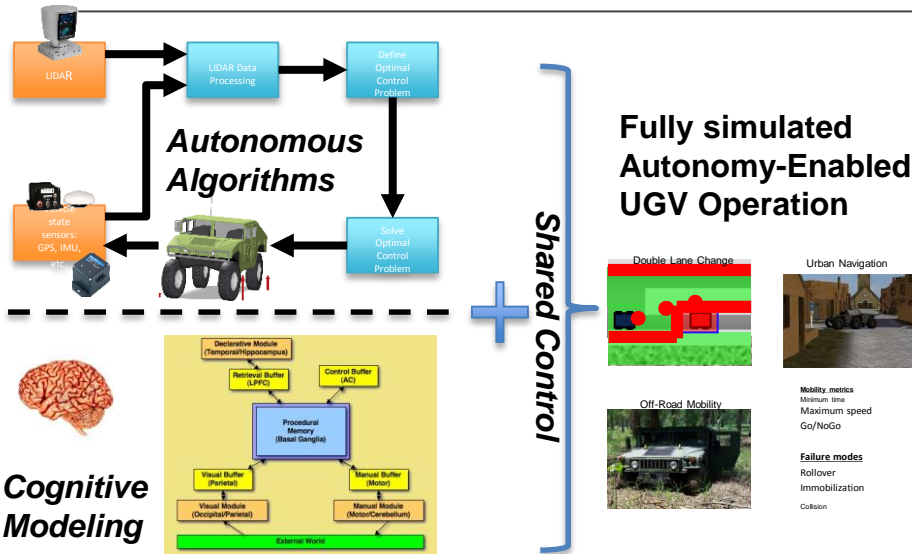
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Determine Autonomy & Latency Relationship to Maximize Mobility

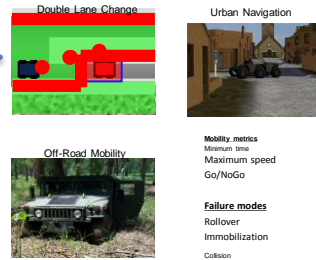
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Autonomy-Enabled Unmanned Ground Vehicle Mobility Simulation



**Fully simulated
Autonomy-Enabled
UGV Operation**



Mobility metrics
Minimum time
Maximum speed
Go/NoGo

Failure modes
Rollover
Immobilization
Collision

Autonomy Algorithm (UMich)

- Powertrain Modeling
- Tire/Soft Soil Modeling
- Variable latency modeling
- Algorithm Sensitivity Analysis
- Code optimization (w/ARL)
- Plant model fidelity study
- Experimental testing

Cognitive Modeling (Alion)

- Driver Model integration and test
- Validation of model to test data
- Simulated teleoperation runs w/latency
- Driver Distraction Modeling
- Higher level cognitive function study

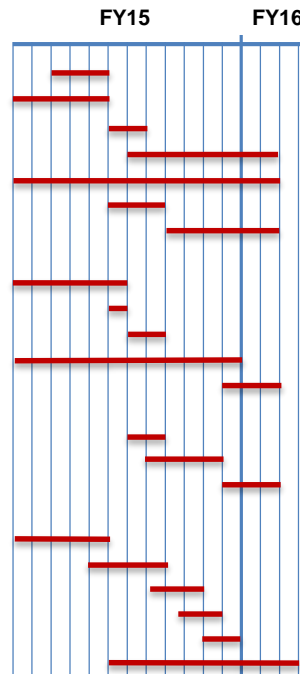
Shared Control Modeling (Alion)

- Integration of blended control algorithm
- Testing of blended algorithm
- Alternative algorithm study

Simulation Environment

(JPL)

- Terramechanics updates
- Autonomous algorithm integration
- Cognitive Model integration
- Shared control implementation
- Scenario testing
- NextGen NRMM Mobility Analysis



Purpose

Develop a simulation capability for analyzing the effect of autonomy on unmanned ground vehicle (UGV) mobility.

Leap-ahead/Disruptive Products/Results

- Realistic simulation of human teleoperation or supervisory control through the incorporation of human cognitive models
- Development of vehicle dynamics-aware autonomous algorithms capable of controlling large vehicles at high speeds
- Integration of shared control algorithms to allow for the simulation of a full range of autonomy levels between full teleoperation and full autonomy.
- An integrated simulation environment incorporating high fidelity vehicle dynamics.

Payoff

Unique capability for analyzing semi-autonomous unmanned ground vehicle mobility

- Cost effective simulation of semi-autonomous control methods without need for expensive / complicated human testing
- Enables autonomy evaluation of large Army vehicles under a variety of scenarios
- Virtual prototyping and design analysis

Transition Milestones

- Deliver integrated simulation environment capable of modeling and analyzing the mobility of a UGV over a full range of semi-autonomous control options (FY16).

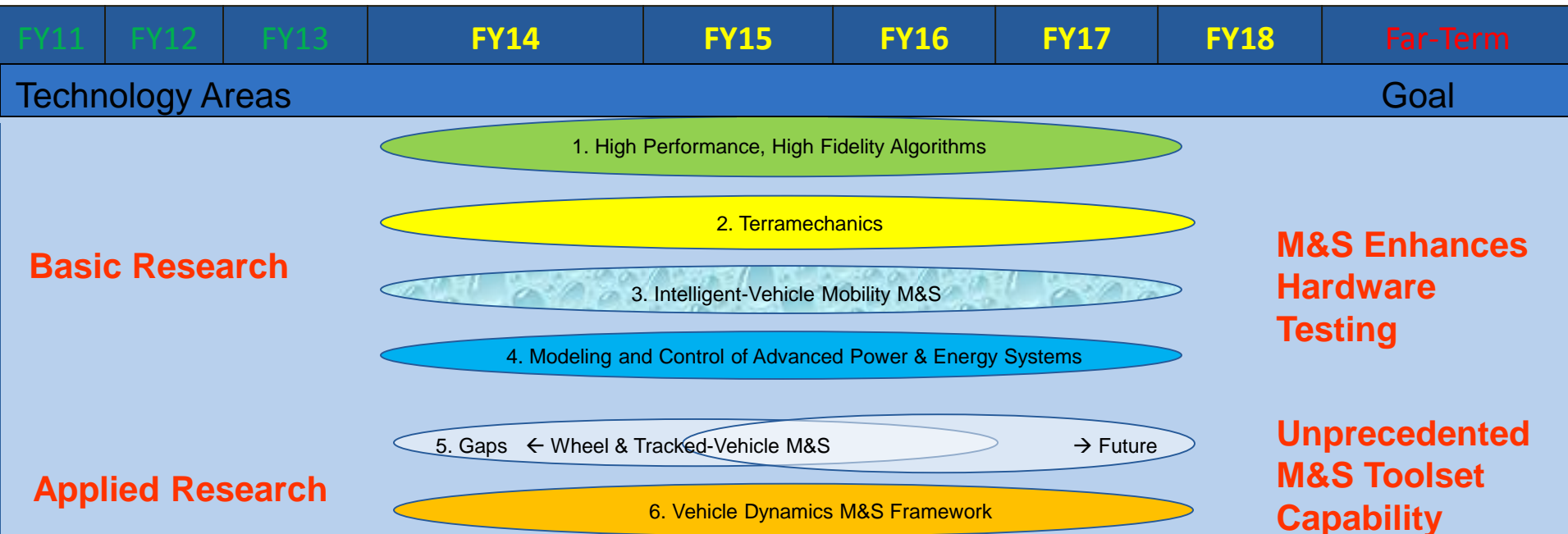
POC: Dr. Paramsothy Jayakumar, TARDEC

Dr. James Poplawski, Alion

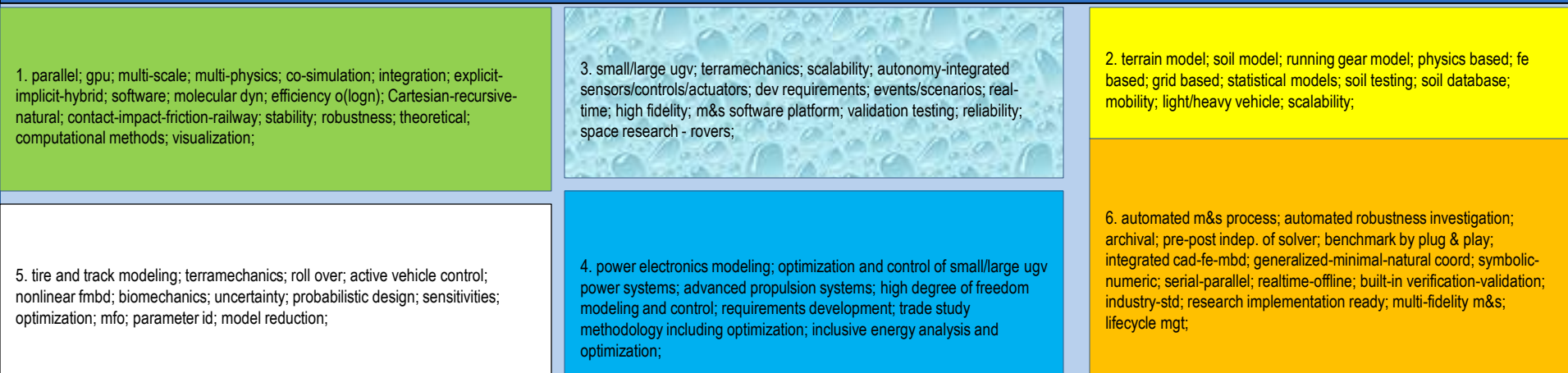
Dr. Abhi Jain, NASA JPL

Dr. Tulga Ersal, University of Michigan

Automotive Research Center Thrust Area 1 Roadmap



Project Ensemble



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P. Jayakumar and D. Rizzo 04 Sep 2012